

2017 Annual Merit Review

Cost-Effective Magnesium Extrusion

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PACIFIC NORTHWEST NATIONAL LABORATORY
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JUNE 2017

Project Overview

Project Timeline

- ▶ **Start: FY15**
- ▶ **Finish: FY18**
- ▶ **73% Complete**

Budget

- ▶ **Project Funding - \$1.2M**
 - FY15 - \$400K
 - FY16 - \$400K
 - FY17 - \$300K
 - FY18 - \$100K

Technology Gaps/Barriers

- ▶ **Use of magnesium alloys in automotive applications limited by:**
 - Cost
 - Strength/Ductility
 - Energy Absorption

Project Partners

- ▶ **National Laboratory**
 - PNNL (Lead)
- ▶ **Tier I Supplier**
 - Magna Cosma International
- ▶ **Academia**
 - Washington State University



Project Motivation

▶ **EERE-VTO MYPP Goal:**

- By 2025, demonstrate a cost-effective 35% weight reduction in passenger vehicles compared to 2010 model (<\$2.16/lb saved).

▶ **VTO Challenges and Barriers:**

- Widespread use of magnesium alloys is cost prohibitive.
- Lower cost magnesium alloys (i.e. absent of rare earth elements) have inadequate strength, ductility and energy absorption properties for structural applications.

▶ **Replacement of Aluminum with Magnesium Alloys**

- >30% weight reduction possible with replacement of components such as bumper beams, crush tips and intrusion beams.



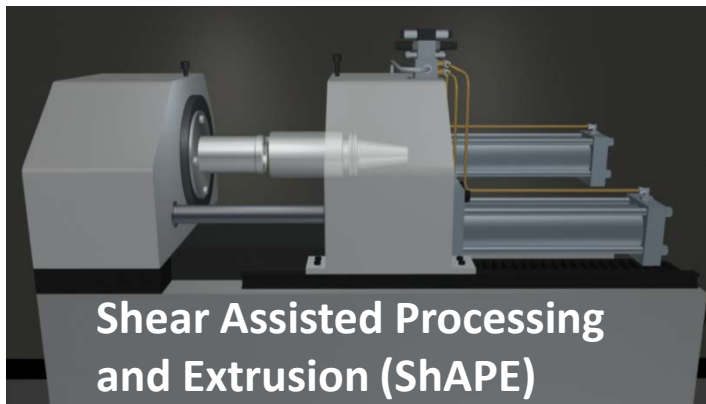
Goals and Objectives

► High Level Goal






- Enable more widespread usage of mass-saving magnesium alloys

► Key Project Goals

- Develop new extrusion method for Mg that does not rely on rare earth elements for their strength, ductility and energy absorption properties
- Determine effect of process parameters on grain size and basal texture
- Demonstrate potential for reduced process cost
- Extrude at industry relevant scale



Project Milestones

Date/Status	Milestone or Go/No-Go
Aug. 2015 <i>Complete</i> 	Task 1: Modeling and Simulation Perform thermal modeling to inform die design
Mar. 2016 <i>Complete</i> 	Task 2: Scaled-Up Extrusion Development Integrate extrusion tooling on existing Friction Stir Welding machine and demonstrate Mg tubing
May 2016 <i>Go/No-Go</i> <i>Complete</i> 	Task 3: Materials Characterization Extrude magnesium alloy tubing with >50 mm diameter and less than 5 micron average grain size
Dec. 2016 <i>Delayed</i> 	Task 4: Mature Scaled-Up Extrusion Process Refine extrusion process on new ShAPE machine. Delayed for procurement and installation of new machine purchased on internal PNNL project.
June 2017 <i>On-Track</i> 	Task 5: Bridge Die Extrusion Demo Integrate portal bridge die tooling onto new ShAPE machine.



Approach: Project Schedule and Progress

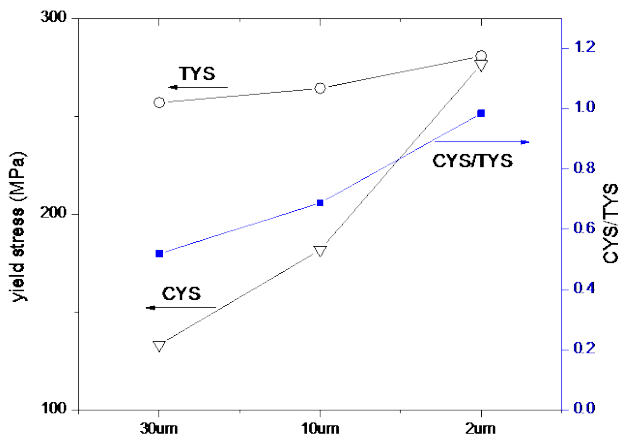
FY		FY15				FY16				FY17				FY18			
Quarter		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Modeling and Simulation																	
FY15 Milestone →	1.1 First Order Models																
	1.2 Detailed Thermal Simulation				Aug 2015												
Task 2: Scaled Up Extrusion System Development																	
FY16 Milestone →	2.1 Establish Scaled Up Extrusion System																
	2.2 Develop Process Parameters																
	2.3 Extrude Mg Tubing >25mm					Mar 2016											
Task 3: Materials Characterization and Model Validation																	
FY16 Go/No Go →	3.1 Microstructural and Mechanical Properties																
	3.2 Tool Face Effects																
	3.3 Model Validation																
	Go/No Go >50mm tubing with <5 micron grain size							May 2016									
Task 4: Mature Scaled Up Extrusion Process																	
FY17 Milestone →	4.1 Process Refinement on New ShAPE Machine							Dec 2016									
	4.2 Microstructural and Mechanical Properties																
Task 5: Bridge Die Extrusion																	
FY17 Milestone →	5.1 Design Bridge Die																
	5.2 Incorporate Bridge Die into Extrusion System																
	Integrate bridge die on new ShAPE machine										June 2017						
	5.3 Direct Extrusion of Mg Alloy using Portal Bridge Die																
	5.4 Process Development																

Transition to new ShAPE machine delayed due to procurement and installation set-backs.

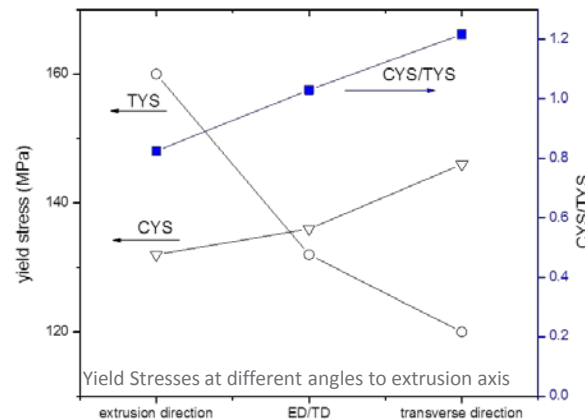


Background: Three Critical Parameters

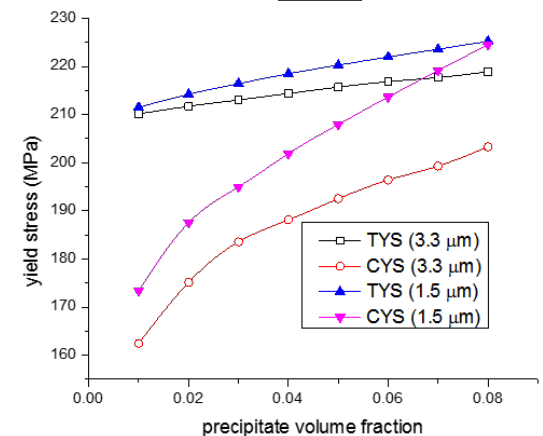
Effect of grain size on CYS/TYS ratio



Determine the Texture to improve CYS/ TYS ratio



Effect of Precipitate Volume fraction on the CYS/TYS ratio



- ▶ The influence of grain size on deformation was predicted by modified ϕ -model and polycrystalline viscoplasticity model.
- ▶ **It was determined that the CYS/TYS ratio increases as the grain size decreases**

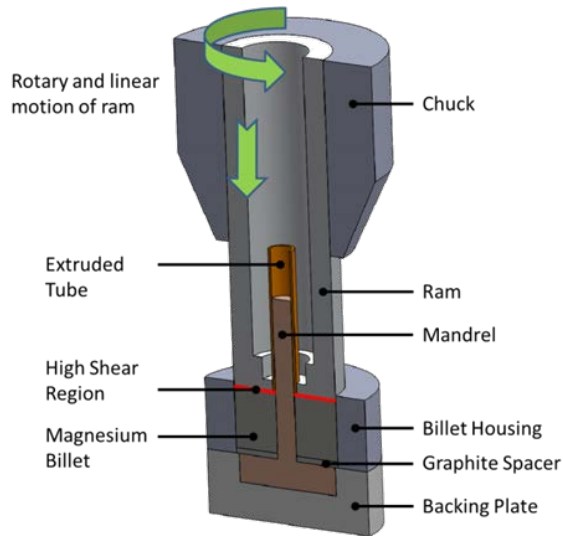
- ▶ The influence of texture on the mechanical properties was determined using the smooth particle hydrodynamics and modified ϕ -model and polycrystalline viscoplasticity model.
- ▶ **It was determined that basal planes should be oriented at least 45° to the extrusion axis**

- ▶ This was simulated quantitatively by coupling a stochastic second phase grain refinement model and a modified polycrystalline crystal viscoplasticity ϕ -model.
- ▶ **It was determined that the mechanical properties are optimum when volume fraction of intermetallics is more than 6% and should be fine.**

*The models were compared with experimental values both in literature and lab tests for ZK60 and AZ31

Background: Shear Assisted Processing and Extrusion (ShAPE)

ShAPE Process



Flute/ Scroll profile on the Ram



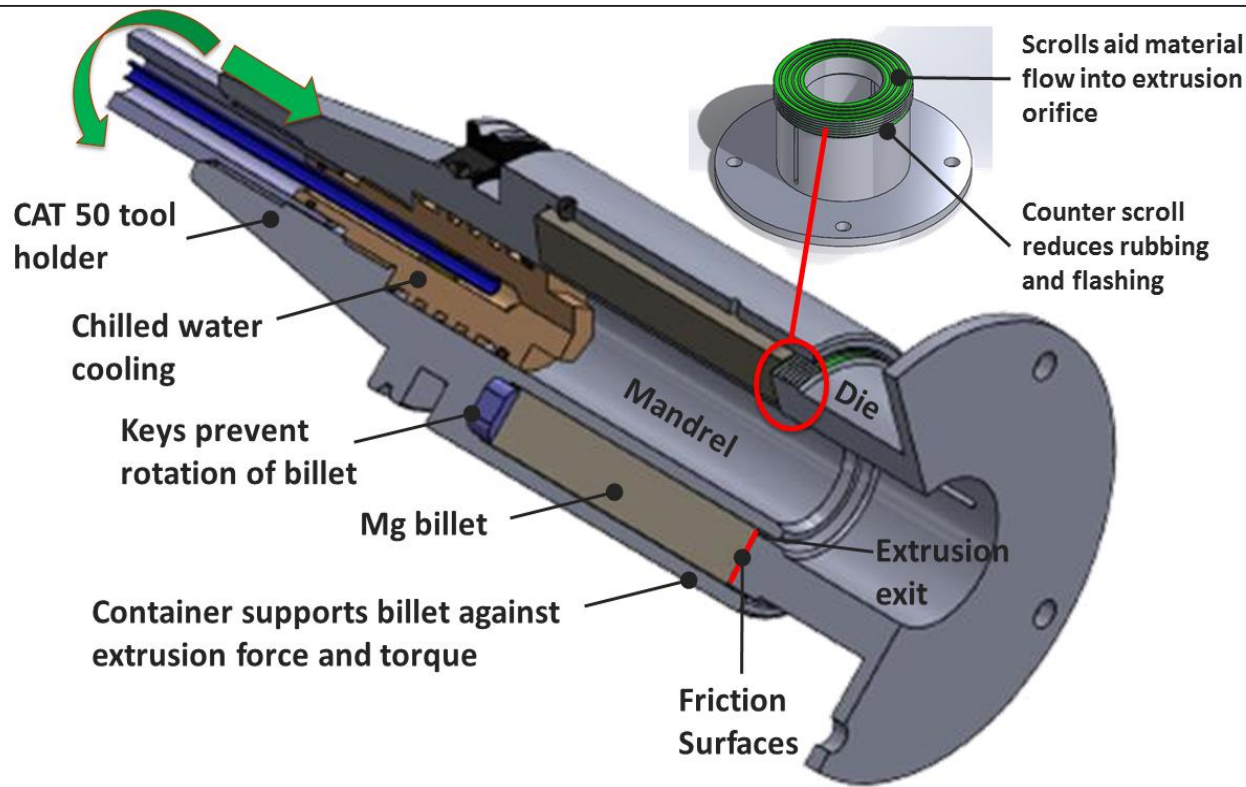
Uniform Dimensions of Extruded Mg Tubes



- ▶ Process is similar to indirect extrusion but **uses a rotating ram** with flutes/scrolls. This also assists in material flow and breaking the intermetallic particles.
- ▶ **The heat required to form is generated by the friction between ram and billet.**
- ▶ The setup was done in an existing Transformation Technology Inc. LS2-2.5 friction stir welding (FSW) machine present at the PNNL.
- ▶ **The extrusion pressures were two orders of magnitude less than that of the conventional indirect extrusion process.**
- ▶ AZ31, ZK60, and Mg-Si alloy tubes were formed using this novel technique.

Technical Approach: Shear Assisted Processing and Extrusion (ShAPE)

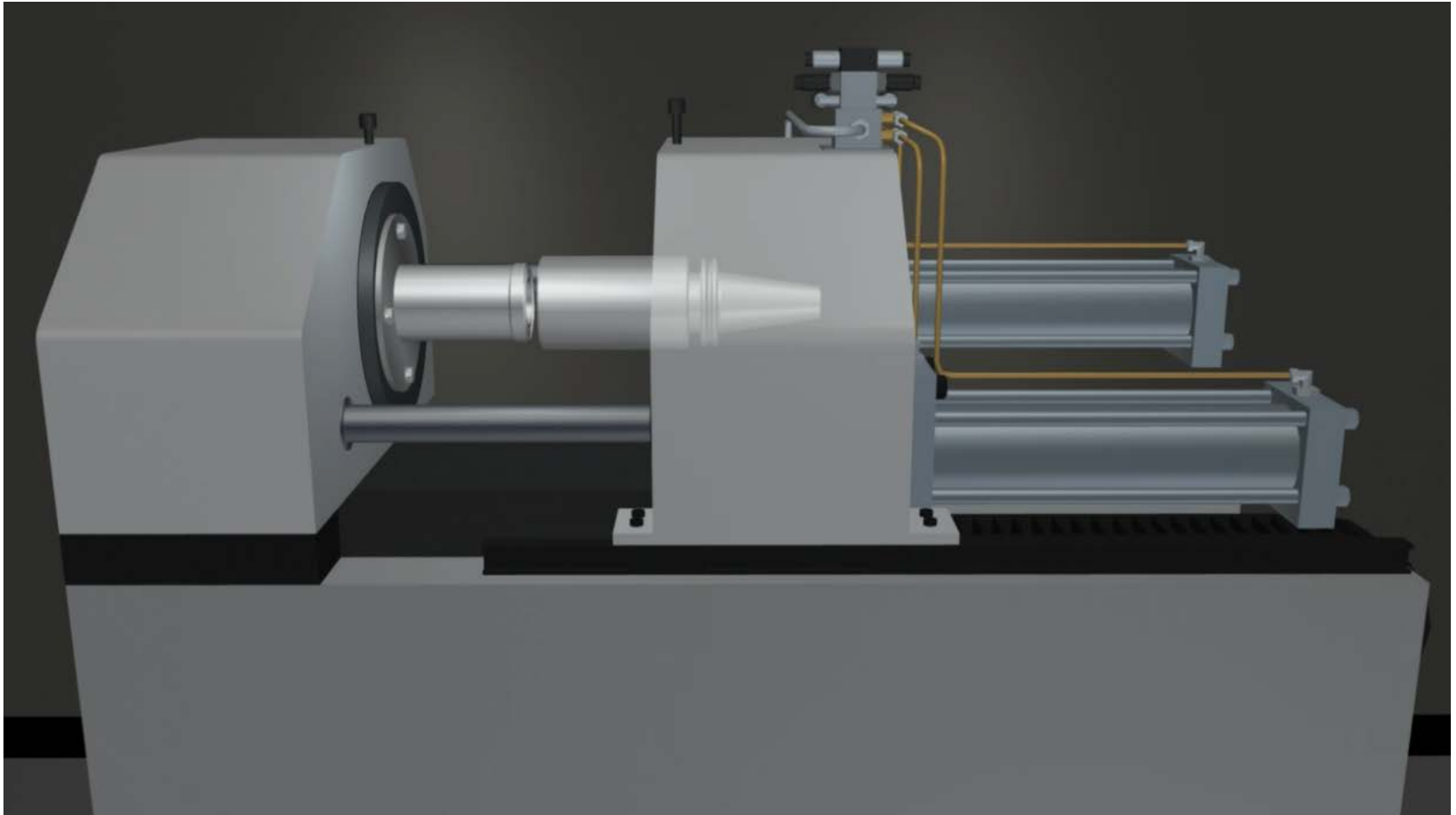
- ▶ In this project, the proof-of-concept experiments are being scaled-up to an industry relevant process.
- ▶ Benefits of ShAPE are being demonstrated at scale.



ShAPE Benefits

- ▶ Grain size and basal texture alignment controlled via process parameters and die design
- ▶ Shear breaks down IMC and disperse uniformly in matrix
- ▶ Reduced process heat and ram force compared to conventional extrusion
- ▶ Potential for increased extrusion rate

Technical Approach: Shear Assisted Processing and Extrusion (ShAPE)



Video of ShAPE Process

Technical Accomplishments: Task 1

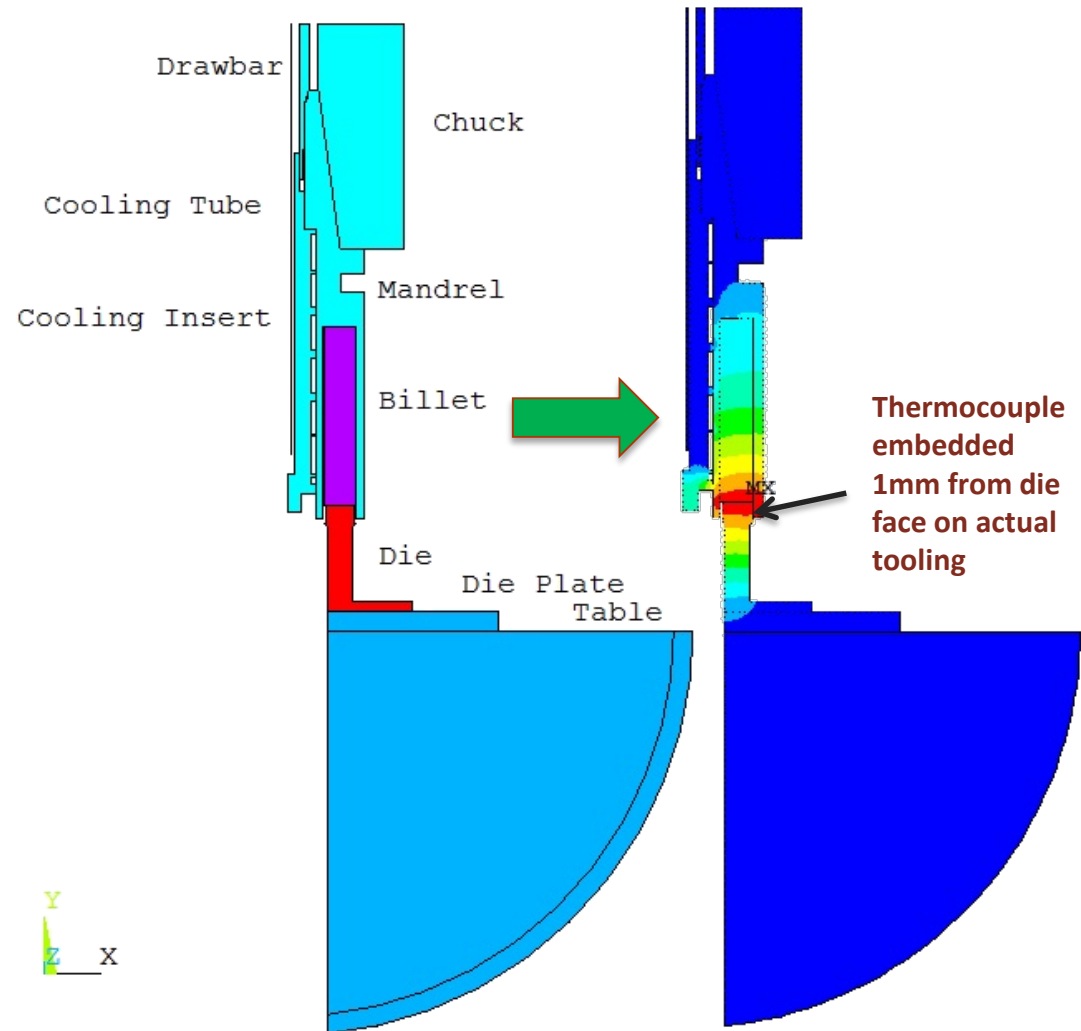
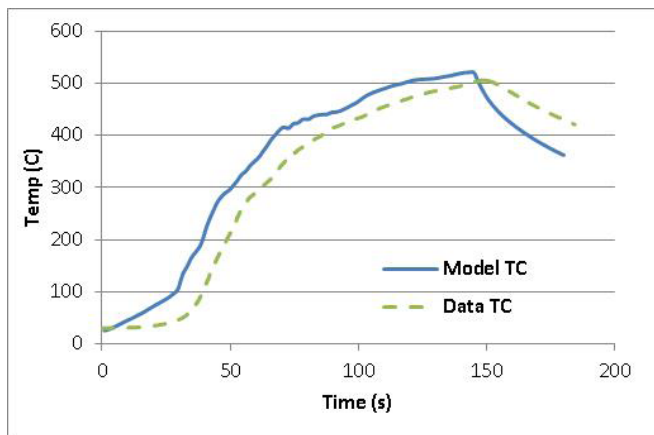
Modeling and Simulation

2D axisymmetric FEA model guided system design:

- Die, container, mandrel, cooling insert, water flow

Predict die face temperature as a function of torque and rpm

Validated model with early experimental trials



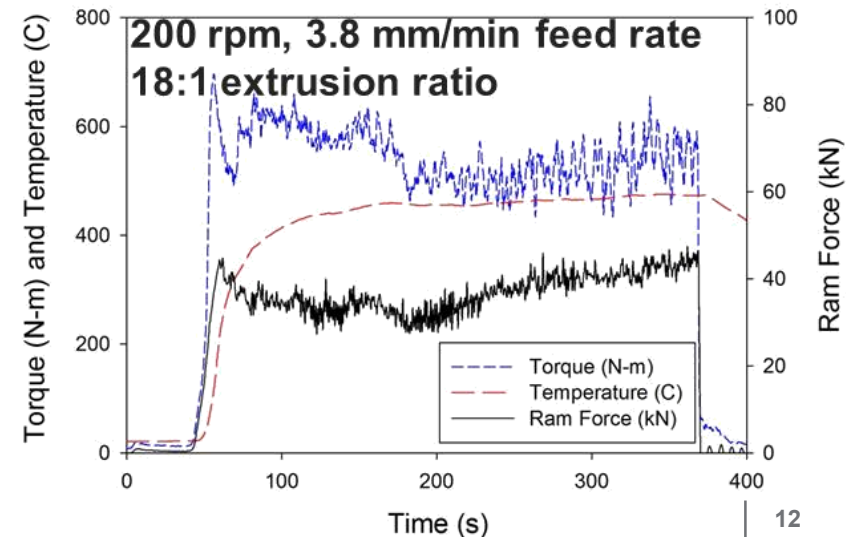
Technical Accomplishments: Task 2

Scaled-Up Extrusion Development

- ▶ Goal of task was to fabricate extrusion tooling, integrate with existing FSW machine, and produce ZK60 tubing >25 mm OD with wall thickness of 1.5 mm.
- ▶ Explore process parameter space of torque, rpm, feed rate, ram force



Process Parameter Development



Technical Accomplishments: Go/No-Go

Fabricate ZK60 tubing with outer diameter >50mm and <5 micron average grain size



- ▶ ZK60 tube fabricated with OD=50.8 mm and wall thickness = 1.52 mm
- ▶ Extremely low electric power input and ram force enabled by ShAPE

■ Power consumption = 11.5 kW

- 550 Nm (400 ft-lb) @ 200 rpm
- No additional heating required
- 11.5 kW \approx residential oven

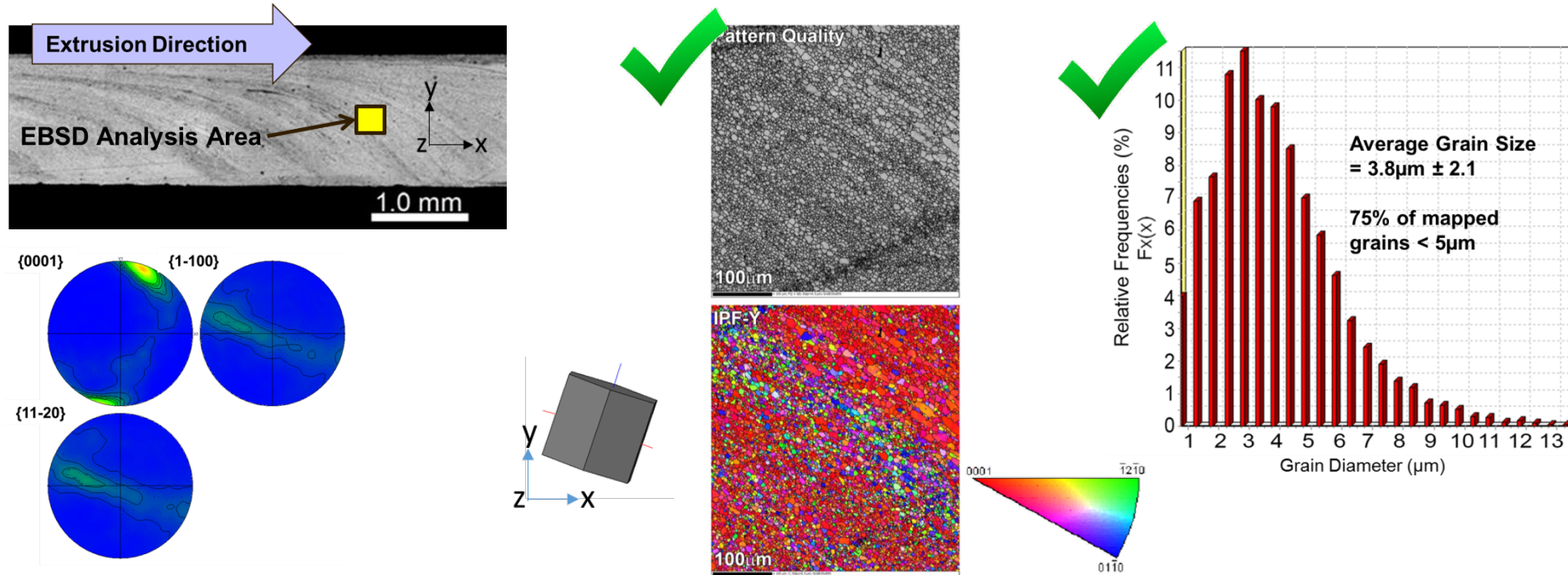
■ Ram force = 40 kN (9000 lb)

- K-factor = 3.33 MPa (0.48 ksi) is >10x lower than conventional extrusion of same cross section
- Enables small CapEx machine



Technical Accomplishments: Task 3

Materials Characterization (Go/No Go)



- ▶ The top side of the specimen was in contact with the die bearing surface while the bottom side contacted the rotating mandrel. During processing, the combined axial and torsional shear, together with material movement aided by scroll features on the die face, result in complex material flow within the extrudate.
- ▶ The analysis found that 75% of the mapped grains were less than $5 \mu\text{m}$ in diameter, with the average being $3.8 \mu\text{m} \pm 2.1 \mu\text{m}$.

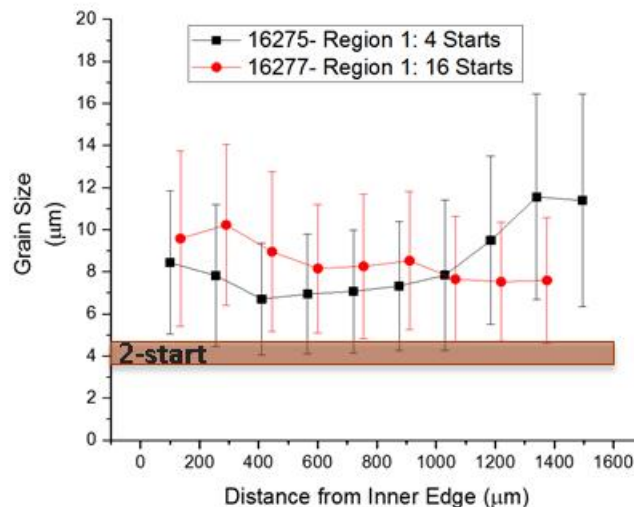
Technical Accomplishments: Task 3

Materials Characterization

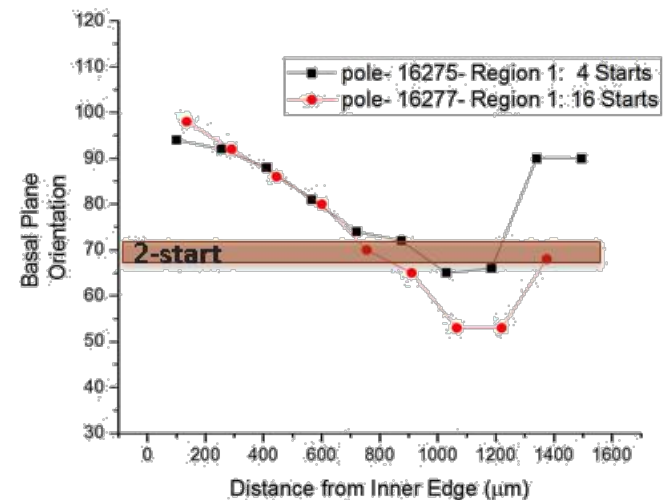


- Explore effect of scroll pattern on grain size and texture development.
- Scroll patterns influence microstructure due to differences in deformation prior to entry into extrusion orifice.

Grain Size



Basal Texture



Technical Accomplishments: Task 3

Materials Characterization

- ▶ Mechanical testing on tube with OD = 50.8 mm and wall thickness = 1.5 mm.
- ▶ Tensile testing per ASTM E-8 performed by Metcut Research, Inc. for UTS and Elongation.
- ▶ Multiple samples of each orientation were extracted along length of 30 cm tube.

Test Direction	UTS (Mpa)	Elongation (%)	Sample Size (n)
Longitudinal (x)	254 ± 2.1	20 ± 1.9	10
45 degrees between (x) and (y)	280 ± 1.0	21 ± 6.4	6
Transverse (y)	297 ± 1.5	25 ± 2.8	11

Up to 50% increase compared to conventional extrusion due to grain refinement and texture alignment





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Response to Previous Year Comments

- ▶ **Project not previously reviewed.**



Collaboration and Coordination

▶ **University Collaborators**

- Washington State University – Perform microstructural characterization of extruded tubing samples.

▶ **Industry Collaborators**

- Magna International – Perform stretch bend testing of extruded tubing when >24" lengths are fabricated. This requires extrusions to be made on the new ShAPE machine.

▶ **Other Teamwork**

- ThumbTool – Design and fabrication of portal bridge dies.



Remaining Challenges and Barriers

► Task 4: Mature Scaled-Up Extrusion

- Extrude several feet of tubing on ShAPE machine in steady-state process at rates relevant to automotive industry
- Maintain uniformity of diameter and wall thickness along extrusion length
- Reduce surface roughness of external tube surface

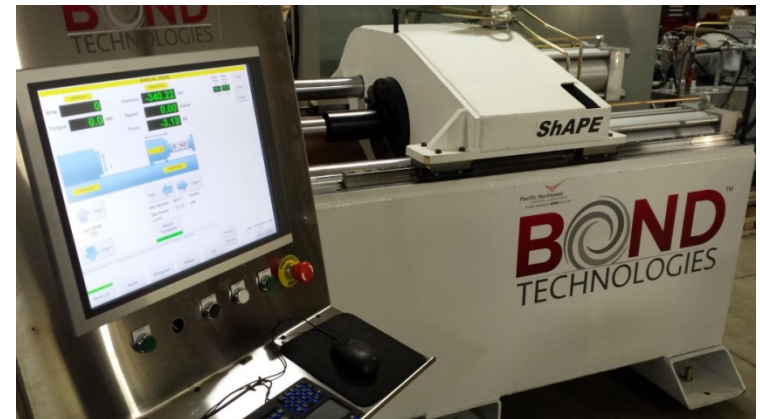
► Task 5: Bridge Die Extrusion

- Portal bridge die still to be attempted using ShAPE
- Challenge to generate high enough back pressure in the weld chamber using ShAPE

Remaining Challenges and Barriers: Task 4

Mature Scaled-Up Extrusion

- ▶ **Equipment purchased through internal PNNL funding. Specifically designed for ShAPE.**
- ▶ **Delayed awaiting start-up and troubleshooting of new ShAPE machine installed at PNNL**
- ▶ **Machine capabilities**
 - Direct and indirect extrusion
 - 4" OD through crosshead
 - 3" OD through motor spindle
 - 200,000 lb ram force
 - 700 ft-lb torque at 1000 rpm
- ▶ **Enables R&D and demonstrations at industry relevant scale**



Remaining Challenges and Barriers : Task 5

Bridge Die Extrusion

- ▶ **The goal of this task is to develop die technology and process parameters for fabricating non-circular cross sections using ShAPE**

- ▶ **Utilizing portal bridge die approach**
 - Material separates through portals
 - Recombines in weld chamber and flows around mandrel

- ▶ **Collaborating with ThumbTool**
 - Tooling currently being fabricated
 - Installation and initial runs schedule for May 2017



Proposed Future Work (planned)

- ▶ **Summer 2017:** Demonstrate several feet of tubing on the new ShAPE machine
 - Identify the parameters to extrude under steady state conditions
 - Extrude at rates relevant to industry

- ▶ **Fall 2017:** Extrude tubes using the Bridgeport dies (FY17 milestone)
 - Determine the challenges associated with using the dies

- ▶ **Spring and Summer 2018:** Process Development
 - Demonstrate repeatability and system robustness
 - Develop extrusion parameters to create the desired grain size and texture



FY16 Project Summary

- ▶ **Scaled-up ZK60 tubing fabricated with 12 inch length, OD of 50.8 mm, and wall thickness of 1.52 mm.**
 - Average grain size of 3.8 μm
 - Basal texture rotated 20° from extrusion direction
 - UTS up to 297 MPa with room temperature ductility of 25%
 - Die scroll pattern geometry shown to affect grain size and texture

- ▶ **There are several advantages of the ShAPE process that lend well to potential cost reduction and scale-up for industry.**
 - K-factor of 3.33 MPa (and thus 40 kN ram force) is >10 times lower than is required for similarly sized tubing fabricated using conventional extrusion
 - Power input of just 11.5 kW was only heat required to maintain temperature
 - Single-step process compared to other multi-step SPD processes such as ECAP, ARB and CEC

- ▶ **Working to transfer R&D to newly installed ShAPE machine.**

Technical Backup Slides

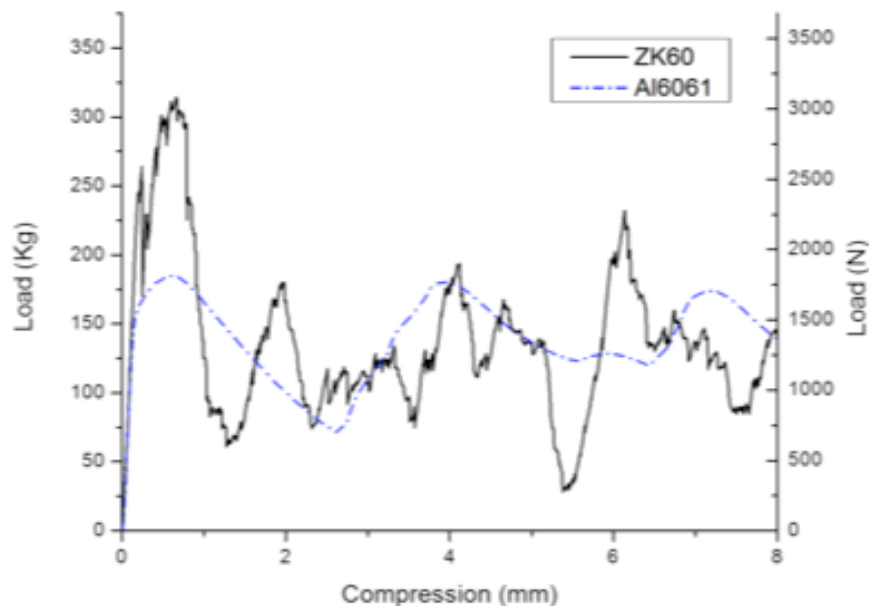


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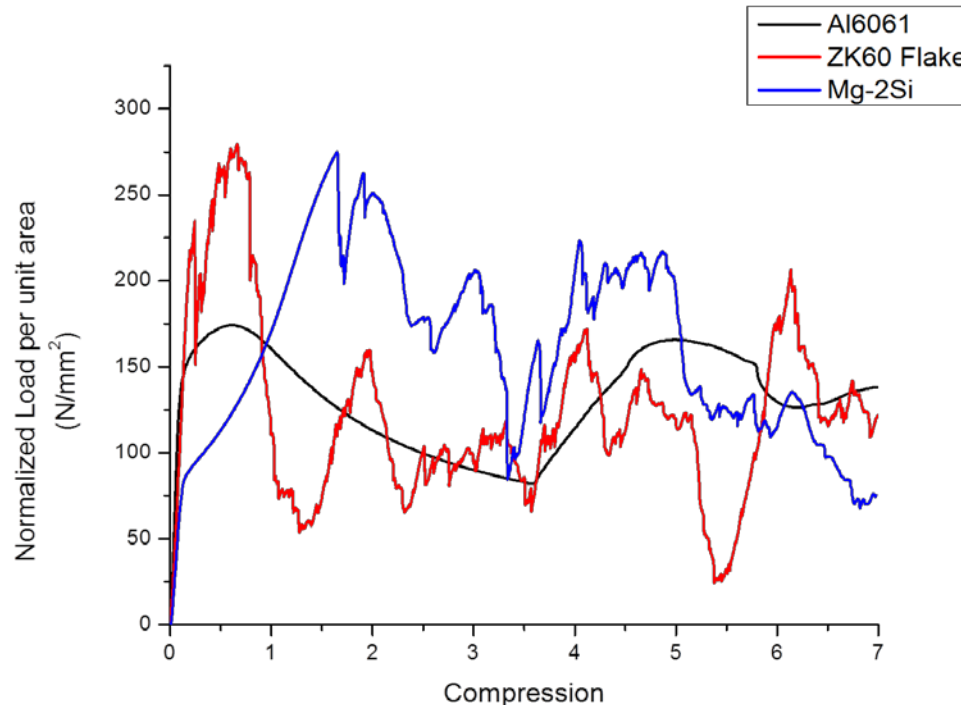
Can Mg be used for Crash Applications?

Crush/Compression Testing of Tubes



- ▶ Earlier work had showed that magnesium alloys produced via rapid solidification show extraordinary strength and ductility
- ▶ Rapidly solidified ZK60 was extruded and were compression tested and compared with AA6061
- ▶ They showed better Specific Absorption Energy and could result into a potential weight saving of over 20%
- ▶ **Rapidly solidified alloys are viable but are very costly**
- ▶ **Crystal Plasticity modeling was used to predict that $CYS/TYS \geq 1$ for the magnesium alloys to work**
- ▶ **So what are the properties we need in order to obtain same strength in more economical way!**

Comparison of Mg-2wt% Si Tube Compression Data with Al6061 and ZK60-Flake

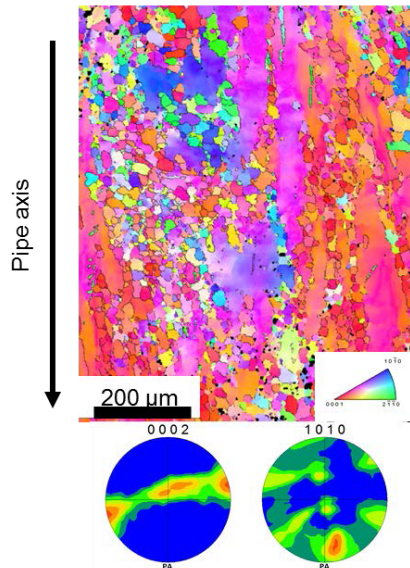


- ▶ Mg-2 wt% Si met the test of energy absorption
 - High shear extrusion can produce desire microstructure that develops high performance properties
 - ZK60A by high shear was similar to Mg-2wt%Si (not shown for clarity)

Microstructure Development in ShAPE- Small Scale Data

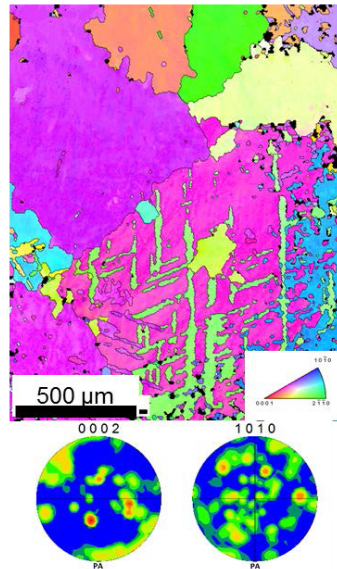
AZ31

Ave. Grain Size:
 $11.36 \pm 11.5 \mu\text{m}$



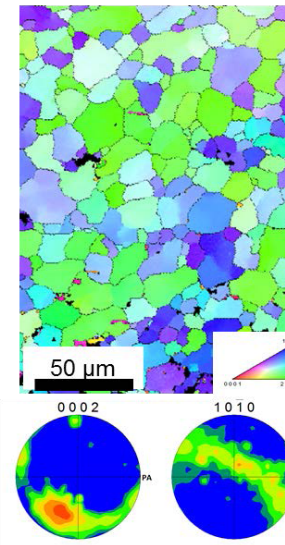
Mg-2%Si

Ave. Grain Size:
 $\sim 1\text{mm}$



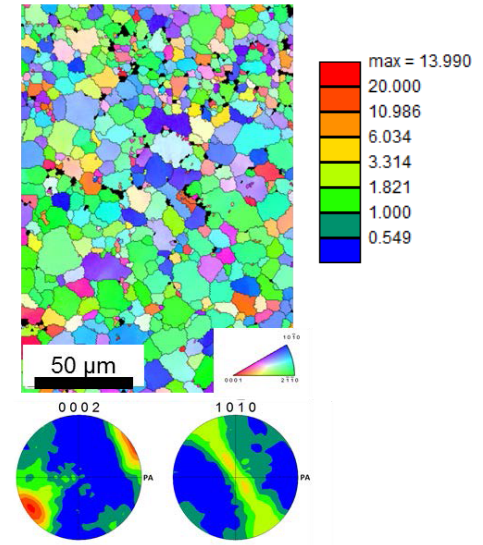
AZ31

Ave. Grain Size:
 $5.52 \pm 0.44 \mu\text{m}$



Mg-2%Si

Ave. Grain Size:
 $3.95 \pm 0.32 \mu\text{m}$



Pipe Axis/Extrusion Direction

- As received AZ31 billet had a bimodal grain size and consisted of elongated grains with pockets of fine grains.
- As-cast Mg-Si Alloys had large grains with what appears to be annealing twins, random texture with Chinese script (eutectic) and blocky Mg_2Si intermetallics.

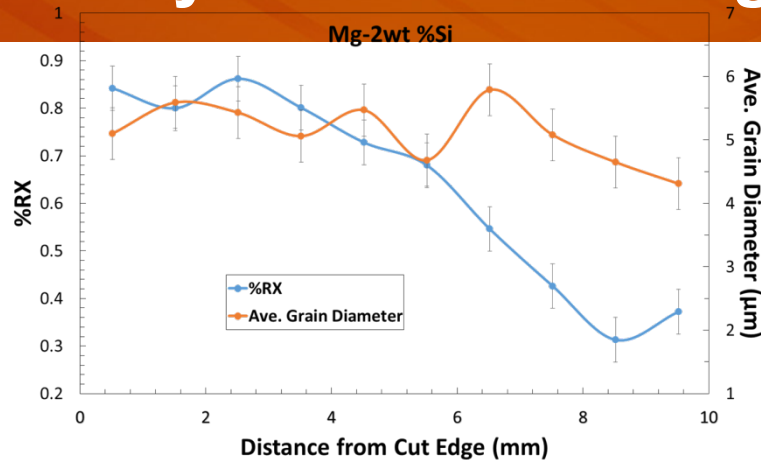
- The grains are refined and equiaxed.
- The basal planes were oriented $\sim 45^\circ$ to the extrusion axis.
- The intermetallics were fractured and uniformly dispersed in the matrix.

Variation of Grain Size and Recrystallization along the Tube Length



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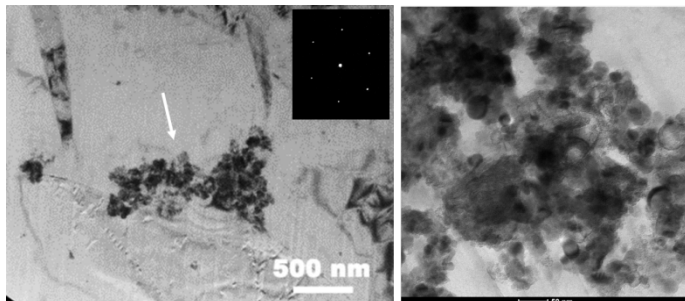
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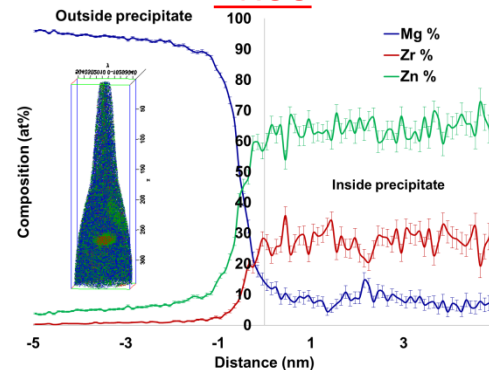
- Recrystallization observed along the tube length was measured by EBSD.
- The equiaxed grain structure and size were retained .
- The fine precipitates are responsible for pinning the grain boundaries and avoiding grain growth.

- The intermetallics in the Mg-Si alloys were visible under the optical microscope; however, verification of intermetallics in ZK60 and AZ31 required the use of TEM.
- Bright field TEM images showing a number of intermetallic particles near grain boundaries (by white arrows). Each Intermetallic particle appears to be about 10 nm in diameter.
- Atom Probe Tomography of the intermetallics on the ZK60 alloys revealed Zn-Zr intermetallics.

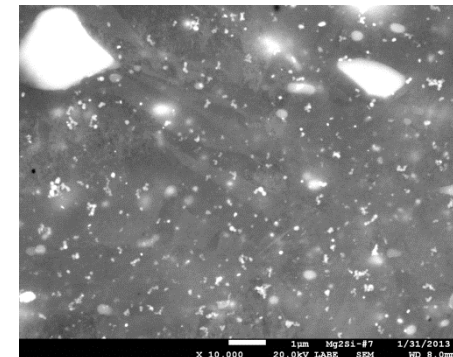
ZK60



ZK60

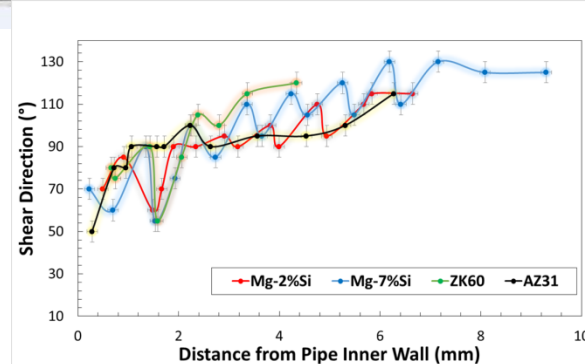
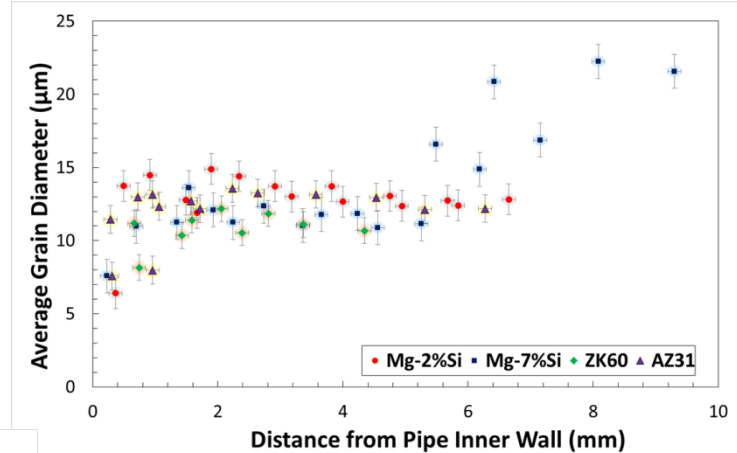
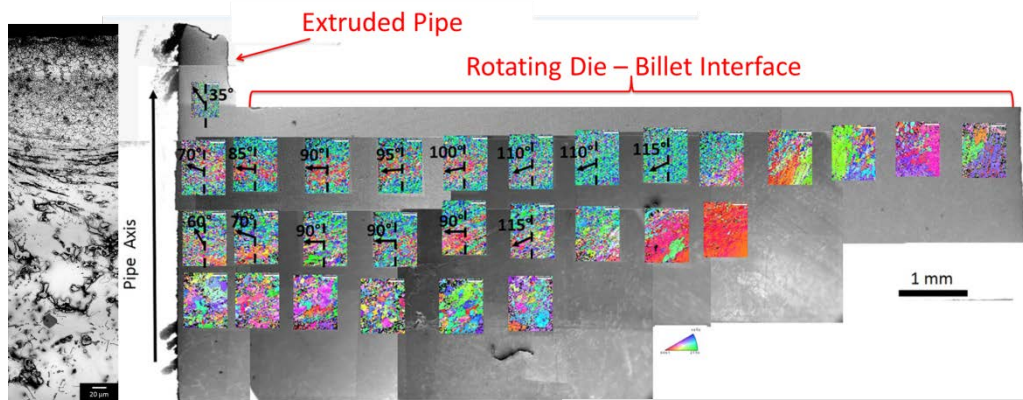


Mg-2Si





Effect of Scrolls on the Material Flow



- ▶ The shearing mechanism is responsible for the change in texture, fracture of the intermetallics, and grain refinement.
- ▶ The basal planes are oriented parallel to the scroll profile and rotate in accordance with the scroll profile.
- ▶ As the material flows through the scroll profile the grain size decreases and the basal plane orient perpendicular to the pipe axis.